

# SSOS: A Moving Object Image Search Tool for Asteroid Precovery

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## ABSTRACT

It is very difficult to find archival images of solar system objects. While regular archive searches can find images at a fixed location, they cannot find images of moving targets. Archival images have become increasingly useful to galactic and stellar astronomers the last few years but, until now, solar system researchers have been at a disadvantage in this respect. The Solar System Object Search (SSOS) at the Canadian Astronomy Data Centre allows users to search for images of moving objects. SSOS accepts as input either a list of observations, an object designation, a set of orbital elements, or a user-generated ephemeris for an object. It then searches for images containing that object over a range of dates. The user is then presented with a list of images containing that object from a variety of archives. Initially created to search the CFHT MegaCam archive, SSOS has been extended to other telescope archives including Gemini, Subaru/SuprimeCam, HST, several ESO instruments and the SDSS for a total of 6.5 million images. The SSOS tool is located on the web at: <http://www.cadc.hia.nrc.gc.ca/ssos>

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## 1. INTRODUCTION

In many fields of astronomy, image archives are of increasing importance. For example, since 2005, more than 50% of HST papers have been based on archival data rather than

PI data<sup>1</sup>. Archival images have become increasingly useful to extra-galactic and stellar astronomers the last few years but, until now, solar system researchers have been at a disadvantage in this respect. While regular archive searches can find images at a fixed location, they cannot find images of moving targets.

This is unfortunate, because it could be argued that archival data is potentially more useful to solar system studies than extra-galactic or stellar astronomy. The full scientific potential derived from the discovery of small solar system bodies (SSSBs) can not be fully realized until precise orbital parameters for those objects can be determined. The object must be tracked over successive nights to obtain an approximate orbit, then over the course of months and years to refine the object’s orbit. But if precovery images containing the object can be found, and the object unambiguously identified in those images, the orbit can be rapidly refined by extending the observed arc into the past.

While a small number of dedicated SSSB surveys have been done and do include the images needed for tracking such objects, the majority of ground based imaging surveys do not include a SSSB discovery component. Indeed, the very requirement of precise orbital determination is exactly why such surveys do not typically include SSSB discovery. For example, over 6000 square degrees of sky have been imaged with the CFHT MegaPrime camera. However, only a small fraction of these images have been carefully searched for SSSBs. These un-searched images are likely to provide a rich repository of astrometric measurements for future SSSB surveys.

The earliest example of the utility of archival data in solar system studies is the discovery of Neptune. While it is well known that the search for Neptune was prompted by perturbations in the position of Uranus, it is less well known that some of the observations of Uranus that went into these calculations were archival. Uranus had appeared (misidentified as a star) in various catalogs going back to 1690 before its discovery as a planet in 1781. Le Verrier (1846) and (Adams 1846) used these critical observations in their calculations to determine the probable location of Neptune.

Of course, archival images can be useful even if the object’s orbit is well known. For example, one may want to generate a light curve for an object. Alternatively, one may want observations of an object at different wavelengths to measure an object’s color. Or again, in the case of binary system, the heliocentric orbit maybe well known, but one may want additional observations to constrain the mutual orbit.

The Solar System Object Search tool (SSOS) at the Canadian Astronomy Data Centre

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<sup>1</sup><http://archive.stsci.edu/hst/bibliography/pubstat.html>

allows users to search for images of moving objects taken with a number of telescopes. SSOS accepts as input either a list of observations, an object designation, a set of orbital elements, or a user-generated ephemeris for an object. It then searches for images of that object over a range of dates. The user is then presented with a list of images containing that object from a variety of archives.

A number of related tools and services already exist. The ESO (European Southern Observatory) archive has a service<sup>2</sup> which allows searches for images of known objects in HST (Hubble Space Telescope) images. The searches are precomputed. Each HST image is searched using SkyBoT (Berthier et al. 2006) for known objects. However the tool is limited to the HST and one can not search for new objects.

The Skymorph service<sup>3</sup> allows users to search for HST images, images from the Near Earth Asteroid Tracking system (Pravdo et al. 1999), Spacewatch (Gehrels & McMillan 1982) images, and a number of older plate catalogs. Input is by object designation or by orbital elements.

The EURONEAR project (Vaduvescu et al. 2009, EUROpean Near Earth Asteroids Research) provides a service which allows users to specify Near Earth Asteroids by name and search the Bucharest Plate archive and the Canada France Hawai'i Telescope Legacy Survey<sup>4</sup> for images.

A tool similar to SSOS has been developed by IPAC, the Infrared Processing and Analysis Center (Groom, private communication). The Moving Object Search Tool (MOST)<sup>5</sup> has been released for use with the Wide-field Infrared Survey Explorer *WISE* telescope. The tool takes as input an object name or a set of orbital parameters which are converted into an ephemeris of the object as seen from the spacecraft. MOST then converts that ephemeris into a series of rectangles on the sky plane which bracket the ephemeris. The rectangles are searched using IPAC's highly efficient positional search. Any images found are further screened first by time and then by a detailed positional match of the ephemeris to the image footprints.

The Pan-STARRS project (Hodapp et al. 2004, Panoramic Survey Telescope and Rapid Response System) is also developing a similar tool to search for Pan-STARRS images.

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<sup>2</sup><http://archive.eso.org/archive/hst/solarbodies/>

<sup>3</sup><http://skyview.gsfc.nasa.gov/cgi-bin/skymorph/mobs.pl>

<sup>4</sup><http://euronear.imcce.fr/tiki-index.php?page=Precovery>

<sup>5</sup>[http://irsa.ipac.caltech.edu/applications/wise/##\\$id\\$=\\$Hydra\relax\\$@@underline{\hbox{~}}\mathsurround](http://irsa.ipac.caltech.edu/applications/wise/##$id$=$Hydra\relax$@@underline{\hbox{~}}\mathsurround)

(Jedicke, private communication) It has not yet been released to the public. The tool generates the positions of all known (or synthetic) objects at the beginning, middle and end of each night. It then fits a quadratic in (RA, Dec) to the positions so that to predict the position of the objects as a function of time through the night. The tool maintains two kd-trees: one for available fields and one for predicted positions. When searching for a given object the field tree is searched and then using the functional motion fit, it predicts which images the object is likely to lie in. For each of the likely images, a full n-body ephemeris is done at the time of the exposure, and the objects position is checked against the image’s coverage.

SSOS has two major advantages over these services: First, SSOS allows searches by a greater number of input methods, allowing searches for precovery images of newly discovered objects. Second, while SSOS was originally developed for searching for images taken with MegaCam on CFHT, it has been extended to include images from several other telescopes. With the exception of Skymorph and EURONEAR, other search tools are currently limited to a single telescope.

Before SSOS can be used, a list of archival images from different telescopes is compiled, as detailed in section 2. The first step of each SSOS query is to convert the user’s input into an ephemeris using one of several methods, as described in section 3. Next, SSOS searches along that ephemeris for images as described in section 5.

## 2. IMAGE HARVESTING

Before any queries can be made, the SSOS image database must be populated. This is done by going to the various telescope archives and harvesting the metadata describing each image taken by the telescope. For each image the SSOS stores the following information:

- Midpoint of exposure time.
- RA and Dec of the image center
- The extent of the image in RA and Dec. Some images are not rectangles and some are not square to the RA-Dec gridlines. In this case SSOS stores the extrema of the images in both coordinates.

For some archives (*e.g.* HST and most of the MegaCam archive), the position of the images is known to within an arcsecond or two. For other archives, the image positions are less well known. To ensure that no image is missed in a search due to a faulty position, the

image extent is increased slightly to compensate; a buffer is added in both RA and Dec. The size of the buffer depends on the typical astrometric quality of an archive. A further buffer of 15 arcseconds is added in both directions to allow for any ephemeris errors.

These buffers increase the completeness but slightly decrease the purity of the searches. When searching for a given object, the search results are unlikely to miss any images containing the object, but may contain a few false positives. In practise, removing all the false positives is impossible. For instance, many of the instruments in the database are mosaic cameras (e.g. MegaCam, SuprimeCam, VISTA), which have gaps between the detectors. False positives will occur if an asteroid happens to lie in a gap during the exposure.

These parameters (time, center and extent) are the minimum required to find the image. When the World Coordinate System (WCS) of an image is available and accurate, this is also stored in order to refine the search as detailed in Section 4.2,

To speed the searches, a bounding box is generated for each image. The bounding box completely encloses the image and is described in integer degrees. Again, to speed the search, the exposure midpoint expressed as a MJD is truncated and stored as an integer.

Images which span the celestial meridian have two entries in the database: one entry describing the part of the of image lying above  $RA=0^\circ$ , and the other describing the part of the image lying below  $RA=360^\circ$ . No special provision is made for images covering the poles, since there are none in the database.

SSOS stores some additional parameters describing each image:

- Exposure time
- Filter
- Telescope/Instrument
- The URL at which the data can retrieved.

The first three of the these give some indication of whether the data will be useful. For example, some users may not want data in a certain filter, others may only be looking for high resolution data, and short exposure images might be too shallow for some objects. The URL will allow the user to actually retrieve the data once found.

Obtaining the metadata for images stored at the Canadian Astronomy Data Centre (CADC), where SSOS is based, is relatively easy. The existing databases describing each image archive are queried directly and the relevant parameters are ingested into the SSOS

database. In some cases the headers of the individual FITS images are retrieved to obtain additional metadata. Currently, the following telescopes and instruments have been harvested from the CADC:

- CFHT (Canada-France Hawai’i Telescope): MegaCam, WIRCam and CFH12K
- Gemini: GMOS images only
- HST (Hubble Space Telescope): WFPC (Wide Field Planetary Camera), ACS (Advanced Camera for Surveys) and WFC3 (Wide Field Camera 3)

Offsite archives must be “scraped” over the web. This can take many forms depending on the archive. The Subaru SuprimeCam image lists are available as simple ASCII text files.<sup>6</sup> The ESO archive can be queried by instrument; while such a query takes many hours, it will return a list of every image made by that instrument. Currently the following telescopes and instruments have been harvested:

- AAT (Anglo-Australian Telescope): WFI (Wide Field Imager)
- ESO-LaSilla 2.2m: WFI (Wide Field Imager)
- ESO-NTT (New Technology Telescope): EFOSC (ESO Faint Object Spectrograph and Camera), EMMI (ESO Multi-Mode Instrument), SOFI (SOn oF Isaac), SUSI1 and SUSI2 (SUperb Seeing Imagers)
- ESO-VISTA (Visible and Infrared Survey Telescope for Astronomy): VIRCAM (VISTA IR Camera)
- VLT (Very Large Telescope): FORS1 and FORS2 (FOcal Reducer/low dispersion Spectrograph), HAWK-I (High Acuity Wide field K-band Imager) NAOS-CONICA (Nasmyth Adaptive Optics System - COudé Near-Infrared CAmera ISAAC (Infrared Spectrometer And Array Camera) and VIMOS (VIsible MultiObject Spectrograph) imaging
- Subaru: SuprimeCam only
- the Sloan Digital Sky Survey DR8 (Aihara et al. 2011).

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<sup>6</sup>*e.g.* [@@underline{\hbox{~}}\mathsurround\z@\\$\relax2009](http://smoka.nao.ac.jp/status/obslog/SUP\relax$)

Images from the NOAO archive, VST (OmegaCam) and the Isaac Newton Group of telescopes will be added in the future.

In principle, data from any instrument can be ingested into SSOS. So far, ingestion efforts have concentrated on image archives from telescopes with larger apertures or larger fields of view. Only data taken in broad band filters is included; narrow band data tends to be too shallow for to be useful for precovery. Finally, only images taken in optical or near-infrared bands has been harvested to date.

Currently, there are 1.6 million images in the SSOS database. Figure 1 shows the area of the sky covered by SSOS. The figure indicates the number of images by greyscale. The darkest patches are covered by at least 40 images. The figure does not indicate the depth or wavelength of the images. For while a substantial fraction of the southern hemisphere has been covered repeatedly by the VIRCAM detector, the exposure time of these infrared images is typically less than a minute. As discussed in section 6, this coverage is sufficient that two thirds of the asteroids in the MPC (Minor Planet Center) database lie within at least one image, and a typical asteroid is covered by 20 images.

### 3. USER INPUT AND CONVERSION TO EPHEMERIS

When arriving at the Solar System Object Search tool website<sup>7</sup>, users have four ways to search for images. In each case, SSOS converts the user’s input into an ephemeris. The four methods of input and conversion are detailed in the following four subsections:

#### 3.1. Search by Arc

In this input method, the user enters a series of observations in MPC format.<sup>8</sup> SSOS uses these observations to determine an orbit and generate an ephemeris from that orbit. The user can select one of two orbit fitting routines: The orbit fitting code of Bernstein & Khushalani (2000) has been set up to automatically convert the observations into orbital parameters (the `fit_radec` code) and use those parameters to produce an ephemeris (the `predict` code). The Bernstein and Khushalani code works best for outer solar system objects; if the arc of a main belt asteroid is too short, it tends to produce spurious results. Therefore, SSOS provides the

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<sup>7</sup><http://www.cadc.hia.nrc.gc.ca/ssos>

<sup>8</sup><http://www.minorplanetcenter.net/iau/info/OpticalObs.html>

new object ephemeris generator from the Minor Planet Center<sup>9</sup> as an alternative. If a user selects this option, the SSOS queries the MPC service automatically. The MPC fits a Väisälä (Väisälä 1939) orbit to the observations and returns an ephemeris based on this orbit. SSOS then uses that ephemeris. This method is slower than the Bernstein & Khushalani fitting because it requires SSOS to make a query (often several queries) to an external service. The ephemeris is generated at intervals of 24 hours. Mauna Kea (observatory code 568) is used as the observing site.

### 3.2. Search by Object Name

In this input method, the user enters the name of an object. SSOS forwards that name to one of two services, either the Lowell Observatory asteroid ephemeris generator<sup>10</sup> or the minor planet and comet ephemeris service at the Minor Planet Center<sup>11</sup>. These services query their databases for an object matching the name, make the appropriate orbital calculations and return an ephemeris to SSOS. SSOS parses the ephemeris from the external services into a format which it can use for the image search.

In addition to using these two offsite services, SSOS can also generate an ephemeris locally. SSOS maintains regularly updated copy of the MPC orbital element database<sup>12</sup>. When a user enters an object name, the local version of this database is queried and the orbital elements are passed to the program `orbfit` of Milani & Gronchi (2010)<sup>13</sup>. which generates an ephemeris.

As with the search by arc option, the ephemeris is generated at 24 hour intervals and Mauna Kea is used as observing site.

### 3.3. Search by Orbital Elements

In this case the user enters the orbital elements of an object: epoch, semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of perihelion and mean

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<sup>9</sup><http://minorplanetcenter.net/iau/MPEph/NewObjEphems.html>

<sup>10</sup><http://asteroid.lowell.edu/cgi-bin/asteph>

<sup>11</sup><http://minorplanetcenter.net/iau/MPEph/MPEph.html>

<sup>12</sup><http://www.minorplanetcenter.net/iau/MPCORB.html>

<sup>13</sup>[http://adams.dm.unipi.it/\\$\sim\\$orbmain/orbfit/](http://adams.dm.unipi.it/$\sim$orbmain/orbfit/)



anomaly. These orbital elements are used as input to the program `orbfit` which returns an ephemeris, again at 24 hour intervals and using Mauna Kea as the observing location.

### 3.4. Search by Ephemeris

This method allows the user complete control over the ephemeris. The user enters a series of times and object positions. Users can cut and paste text into the service. This method is useful if the user has any concerns about the positional accuracy of any of the previous methods. This might be because the object being searched for is near enough to the earth that the parallax will significantly affect the objects positions. Alternatively, the object’s apparent motion might be irregular enough that the the linear daily interpolation scheme is insufficiently accurate. Finally, the user might have concerns about the accuracy of the program generating the ephemeris.

### 3.5. Ephemeris Accuracy

For the first three types of searches, the ephemeris is generated with Mauna Kea as the reference location because two of the most useful instruments in the SSOS database are located there. In this sort of search, usefulness can be quantified as mirror area  $\times$  field-of-view  $\times$  years in operation. MegaCam on CFHT and SuprimeCam on Subaru are the clear leaders. Mauna Kea is also the location of Gemini North. However the rest of the telescopes are at other locations on the earth, while HST is in orbit. How much does the assumption of Mauna Kea as the observing location affect the ephemeris?

For main belt asteroids, the assumption will introduce errors of at most  $\sim 10$  arcseconds. The parallax error is on the order of 1 earth radius divided by 1 AU (approximately the closest approach of a main belt asteroid), which is 8 arcseconds. For more distant objects, such as Kuiper Belt Objects, the error will be significantly less. In the extreme case of near-earth objects, the parallax error can be much greater, but for short periods. In the vast majority of cases, the 15 arcsecond buffer described in Section 2 is sufficient.

Again, for the first three types of searches, the ephemeris is generated at 24 hour intervals. For times between these points, linear interpolation is used to determine the location of the object, as detailed in the following section. This is done for reasons of speed. But how much is the ephemeris accuracy affected relative to — for example — an hourly ephemeris?

This was tested by generating ephemerides at 15 minutes intervals for a few key objects: a KBO, a main belt asteroid and an Apollo: Pluto (134340), Ceres (1) and Eger (3103). The

positions were compared to the results of the linear interpolation described in Section 5. The size of the resulting offsets were smaller than the parallax errors above: less than an arcsecond for KBOs, a few arcseconds for main belt asteroids and, while generally small for the Apollos, occasionally as large as 2-3 arcminutes. Again, the buffers added to the image extents described in Section 2 should be sufficient in most cases.

In exceptional cases, users will have to use the direct ephemeris input method described in section 3.4. Alternatively, if an increased false positive rate is acceptable, they can increase the positional uncertainty as described in the following section.

## 4. ADDITIONAL INPUTS

### 4.1. Positional Uncertainty

In addition to ephemeris information, the user can also specify positional uncertainty information. This is useful if an object’s ephemeris is not perfectly known. Instead of searching only for images containing the object’s assumed location, the search is broadened to include images nearby. The search is increased from a point to a search box whose size is specified by the user. In most cases, the size of the search box is fixed. However, if an arc search using the Bernstein & Khushalani code is selected, then the user can choose to use the error ellipse generated by the code. The search box at each location grows to contain the error ellipse.

### 4.2. Positional Resolution

The MegaPrime mosaic camera on CFHT consists of 36 separate CCDs. Each MegaCam image is large: 700Mb (300Mb in compressed format). Downloading a large number of the these images can be time consuming depending on the user’s bandwidth. However, the images are stored in Multi-Extension FITS format. It is possible to download a single extension (corresponding to a separate chip) from the CADK. At about 16Mb in size, it offers an attractive alternative to the full image. Therefore, SSOS offers an option to resolve the search down the extension level for MegaCam images. This option is only available for the MegaCam images which have been calibrated using the MegaPipe pipeline, currently about 75% of the total MegaCam archive. When this option is active, the search returns a link to the image extensions which likely contain the object being searched for. If the positional uncertainty is specified (as in Section 4.1 above) links to all the CCDs spanned by the error box are returned.

Similarly, SSOS also has the option to resolve down to the pixel coordinates within a single chip. The stored world coordinate system for that chip is used to convert the RA and Dec of the object to an XY pixel location which is returned the user.

## 5. SEARCHING ALONG THE EPHEMERIS

Once the first step, that of generating an ephemeris, has been accomplished, the next step is to match that ephemeris to the database of images. The ephemeris is converted to a temporary database table. Each interval in the ephemeris becomes a row in the table, with start and end times and positions. A bounding box is generated for each row, covering the full span in time and position. For speed, this bounding box is expressed as integer days (for the time) and integer degrees (for position). When the object moves across the first point of Aries, two row are added, one each describing the position of the object on either side of the celestial meridian. If the time interval spans multiple days (for example if the user generated ephemeris has been produced at weekly intervals), additional rows, one per day, are added to this table. This temporary table is comparatively small. If the ephemeris is sampled daily, just under 8000 rows suffice to cover the time span from the earliest image in the SSOS database to the present. Building the temporary table takes 2-3 seconds for a full 20 year span.

The ephemeris table is then cross matched to the image table; in the terminology of relational databases, they are “joined”. The integer bounding boxes of the ephemeris and the images are matched first. If the bounding boxes of an ephemeris and an image match, the object’s position is calculated more accurately at the image’s exposure midpoint by linearly interpolating the ephemeris. The linear interpolation is key to keeping the queries reasonably fast. Doing a full orbital prediction for each of the images is not feasible. This is sufficiently accurate for the majority of queries, where the object either moves slowly or in a fairly straight line. For faster moving, nearby objects, it may be necessary to supply the ephemeris sampled at shorter time steps, as discussed in section 3.5. If a spline method is used (rather than linear interpolation), the positional accuracy increases, but only by a few percent and at considerable computational cost. A typical cross match takes 0.3 seconds to match a 20 year ephemeris to a 1.6 million images.

## 6. RESULTS AND PERFORMANCE

The results page presents the user with a table listing the image name, exposure midpoint, filter name, exposure time, the objects position at exposure midpoint, the image target name and links to more metadata. If possible (for example if the image is hosted at the CADC), SSOS provides a direct HTML link to the image. For data centers such as SMOKA and ESO, which operate on the request-stage-retrieve model, SSOS provides a link to the request webpage for that image.

In addition to providing a table, SSOS provides a plot showing the location of the object on the sky, with a line showing the objects location and dots showing matching images. This information is also made available as a ds9 regions file.

The speed of the search depends on which ephemeris method is used and the time span being searched. The fastest example is if the orbit fitting method of Bernstein and Khushalani method is used and the time span is short: a few months before and after the input observations. This would be the span useful for precovery of a newly discovered object. In this case, the search would require less than a second to generate the ephemeris, build the temporary table and match to the SSOS image table. On the other hand, if one searches by object name sets the span to the full twenty year span of the SSOS image database, and requests that the MPC be used to generate the ephemeris, the search will take longer. The MPC queries can take 10 or more seconds (depending on the load on the MPC servers), it will take 2-3 seconds to generate the temporary ephemeris table, and the cross matching will take a second. This represents the slowest possible search.

How likely is it that SSOS will find images of a particular object? And how many images of an object is it likely to find? Obviously, if a typical search does not return any images, the service is not very useful. This was investigated by searching for images of 566 253 objects from the MPC orbital element database. It was found that, of these searches, 384 786 returned at least one image, *i.e.* just over two thirds of the searches were successful. The results are shown in figure 2. The number of images returned by the searches is shown as a histogram. Searches returning no images are shown as a separate histogram bar. In some cases, several hundred images are returned. If only the successful searches (*i.e.* the searches returning at least one image) are considered, the average number of images returned is 30. The average number of images returned over all searches is 20 (including the third of the searches that returned nothing).

Note that this is just the number of images returned, which may not be a good indication of how many useful observations may be derived from these images. SSOS will only find the images containing an object. It does not in general find the position of that object in the

images. Where the orbital parameters are poorly known, positional uncertainty may make it difficult to find the object in question. Indeed, if the position is poorly known and the image’s field of view is small, all that SSOS can say is that the image probably contains the object. If there are many moving objects in the images, it may be hard to unambiguously identify the object in question. Unless there are multiple images of the object close together in time, it will be hard or impossible to identify the object. Alternatively, there may be enough images coincident in position and time, but taken in different wavelengths, making it harder to identify the moving object. As noted in section 2, some of the instruments described in SSOS are mosaic cameras with gaps between the detectors; SSOS does not describe the footprint of the cameras in detail, so objects may fall between the gaps. Finally, there is no guarantee that the images returned are deep enough to detect the object, even if it covers the correct patch of sky.

## 7. USAGE

To date, SSOS has been used successfully in a number of projects:

Parker et al. (2011) used the tool to locate additional data of wide binary TNOs. SSOS found images in the HST and Gemini archives that were used to constrain the mutual orbit of the binaries.

The SSOS tool was used by the Canada-France Ecliptic Plane Survey (Petit et al. 2011, CFEPS) project in two ways. First, they used the tool to retrieve the survey’s images of particular KBOs. This allowed the rapid re-analysis of the discovery data to search for binaries among the CFEPS KBOs (Lin et al. 2010). Secondly, the ability to easily return to the search data allows members external to the original survey to enhance the survey dataset. The search tool was also used to look for, and find, pre- and post- discovery images of the KBOs discovered by the CFEPS project.

SSOS is also part of the KBO search in the Next Generation Virgo Survey (Ferrarese et al. 2011, NGVS). While the main purpose of the NGVS is the study of the properties of galaxies in the Virgo cluster, the same data is being used to search for KBOs. SSOS is used to search for additional images of the newly detected KBOs.

Alexandersen et al (in preparation) discovered a Jovian moon in 2010. Using SSOS and its user-generated ephemeris feature, they were able to find precovery images dating back to 2003 from the CFHT MegaCam archive.

Finally, Fraser et al. (in preparation) used SSOS for precovery of Kuiper belt ob-

jects as part of a follow-up program of objects discovered in Fraser, Brown, and Schwamb (Fraser et al. 2010). These targets are part of a large sample used to determine the size distribution of different Kuiper belt dynamical populations, which will help constrain the formation history of the outer Solar system.

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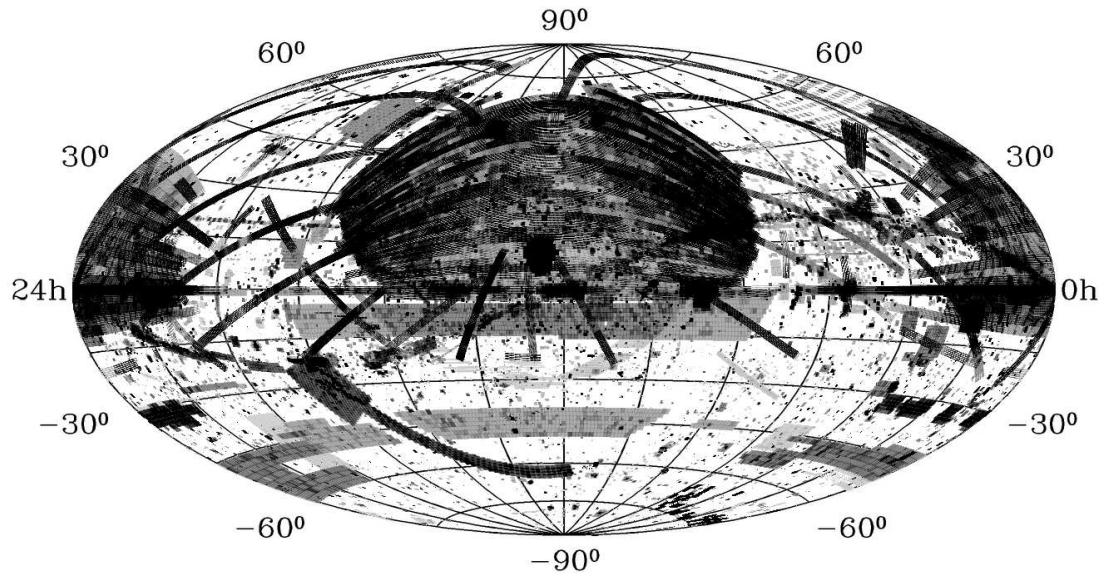


Fig. 1.— Area of the sky covered by SSOS. The greyscale gives an indication the number of images covering a particular spot on the sky, with a single image being represented by the faintest grey, and 40 or more images being indicated by solid black



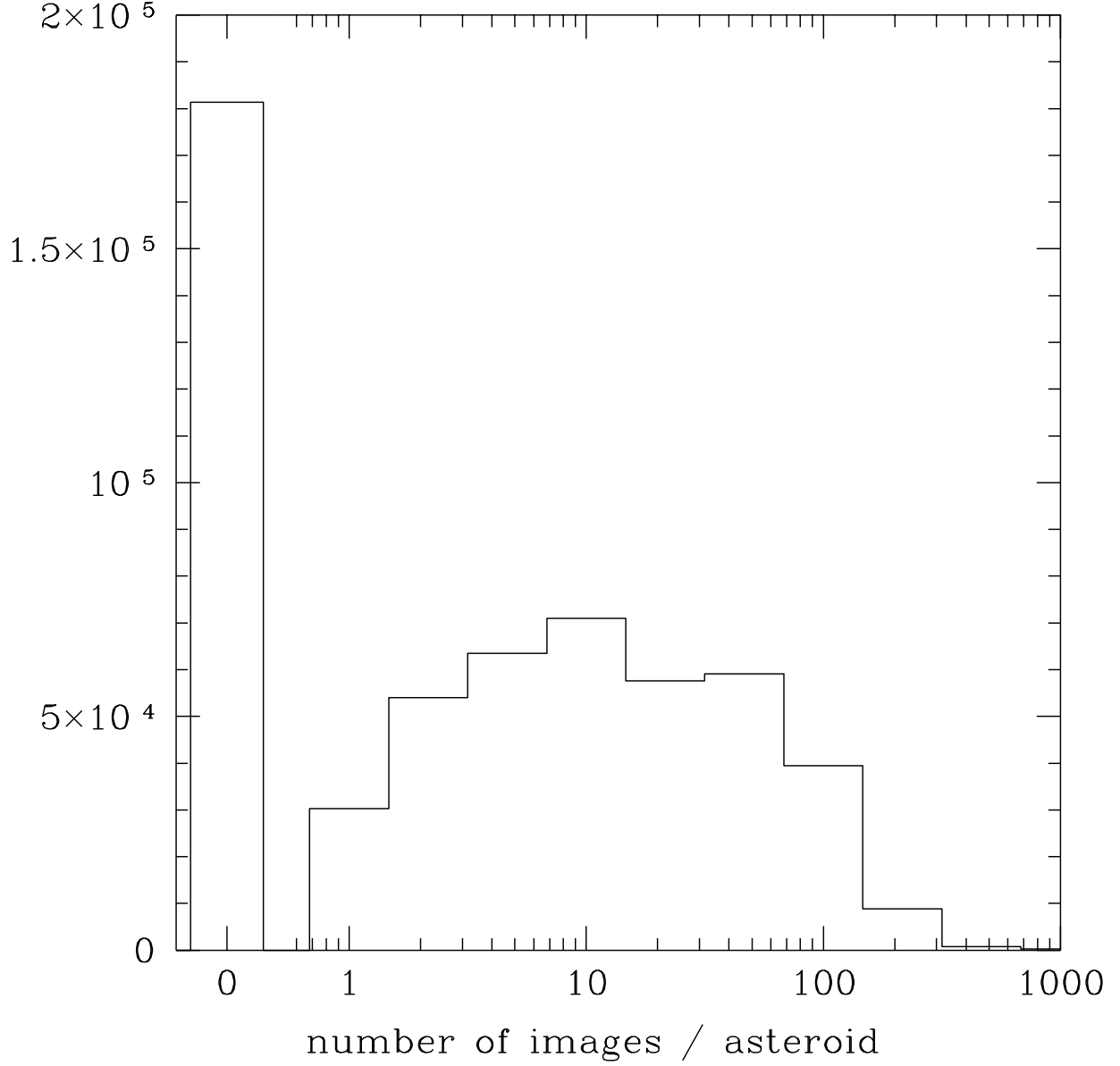


Fig. 2.— Number of images containing an asteroid. The figure was generated by feeding all the objects in the MPC orbital element database into SSOS and plotting the number of returned images as a histogram. Note that the axis is logarithmic. Searches returning no images are shown as a separate histogram bar. Two thirds of the searches return at least one image. On average, an image search for given object will return 10 images, but with considerable scatter.